The evolution of gas in and around galaxies

Jim Geach

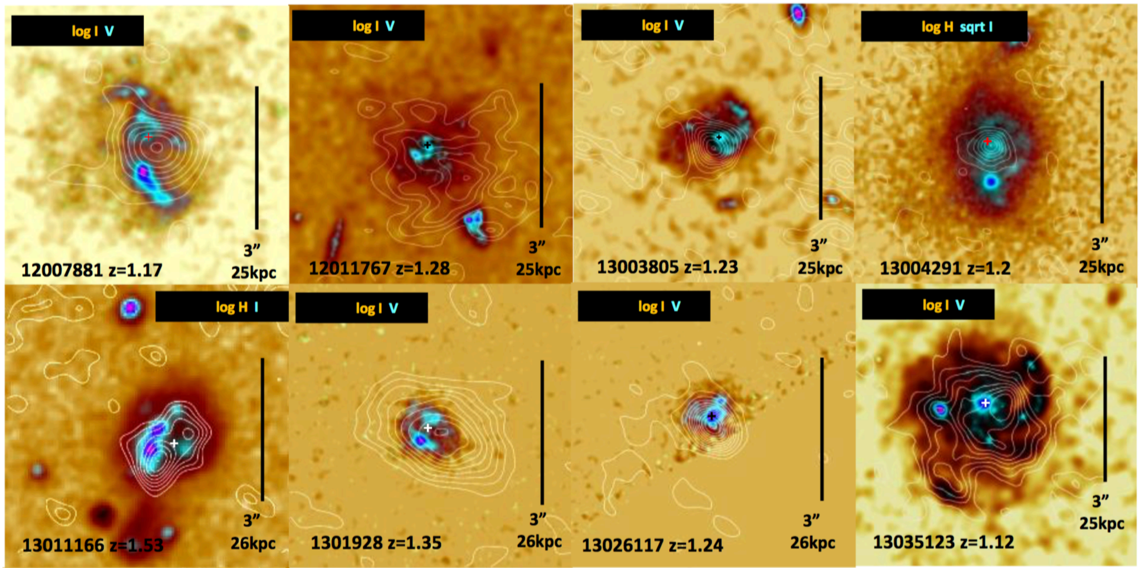
Galaxy Evolution Across Cosmic Time, Paris June 2017

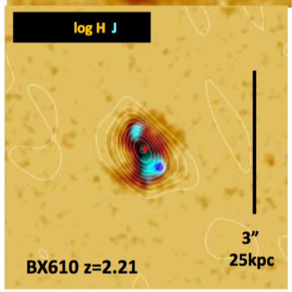
University *of* Hertfordshire

THE ROYAL SOCIETY

Cosmological context

Feedback’s impact on molecular gas





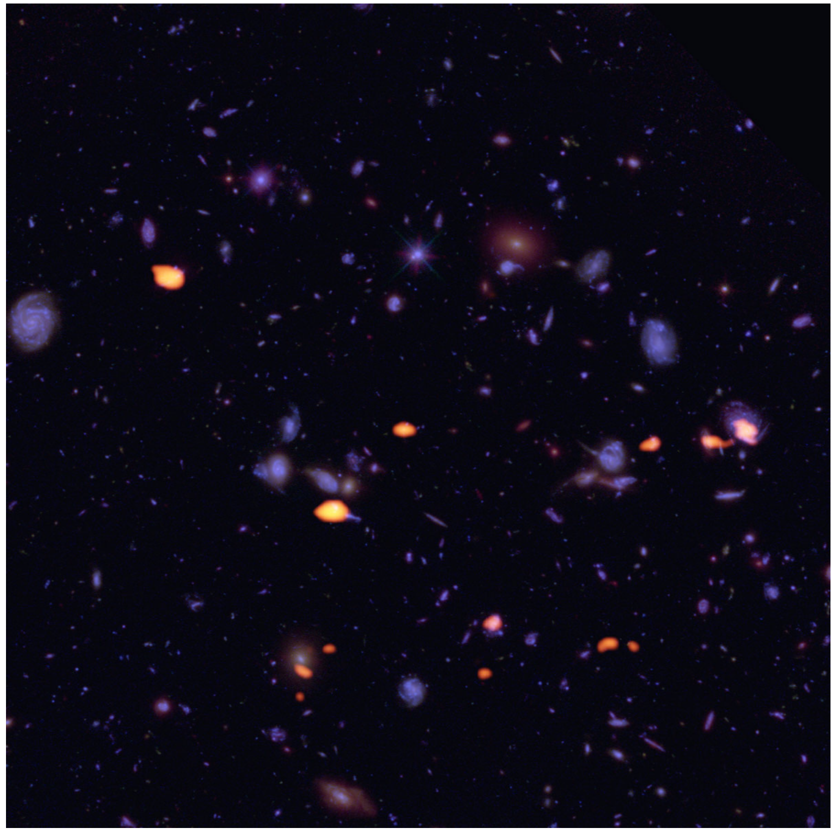
Tacconi et al. (2013, 2017)
Genzel et al. (2013, 2015)

PHIBSS

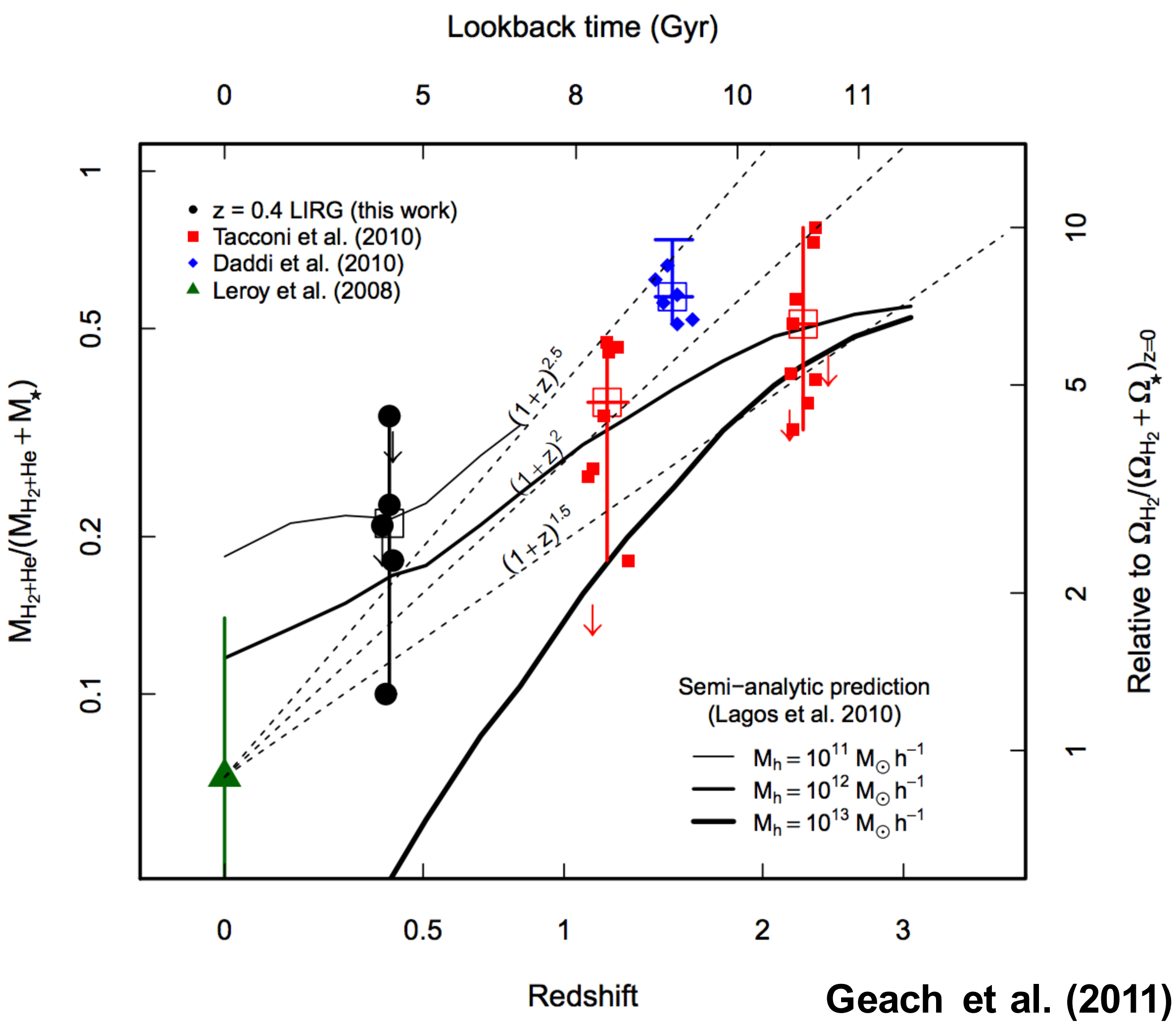
Direct observations of cold gas in galaxies at the cosmic peak are now (nearly) routine

Walter et al. (2016)
Decarli et al. (2016)

ASPECS



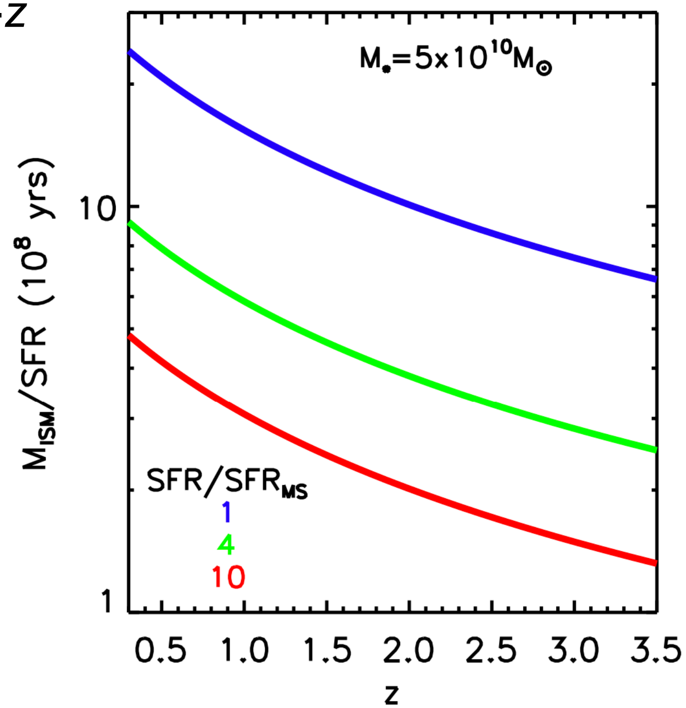
The epoch of molecular gas

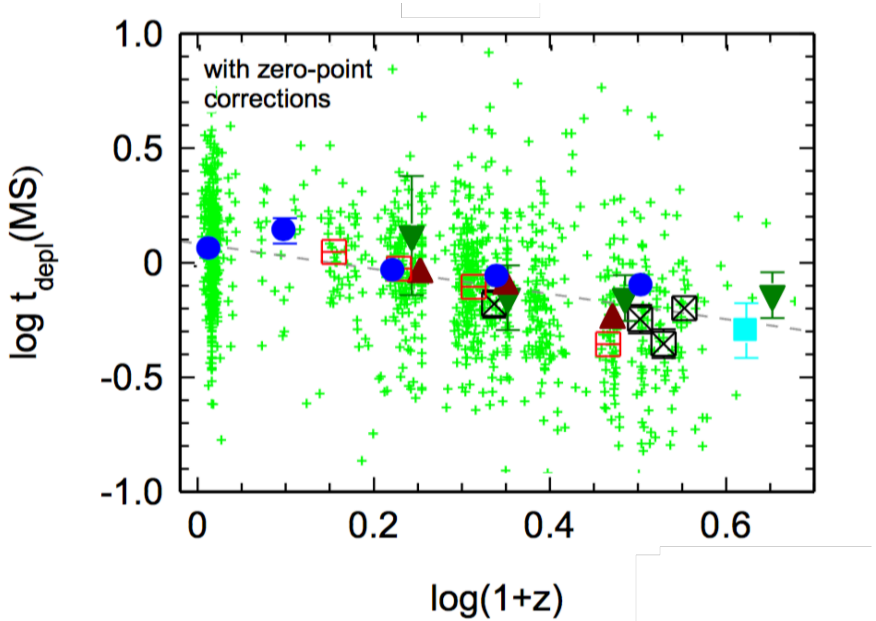


Geach et al. (2011)

Does a higher (total) gas fraction necessarily drive higher star formation efficiency?

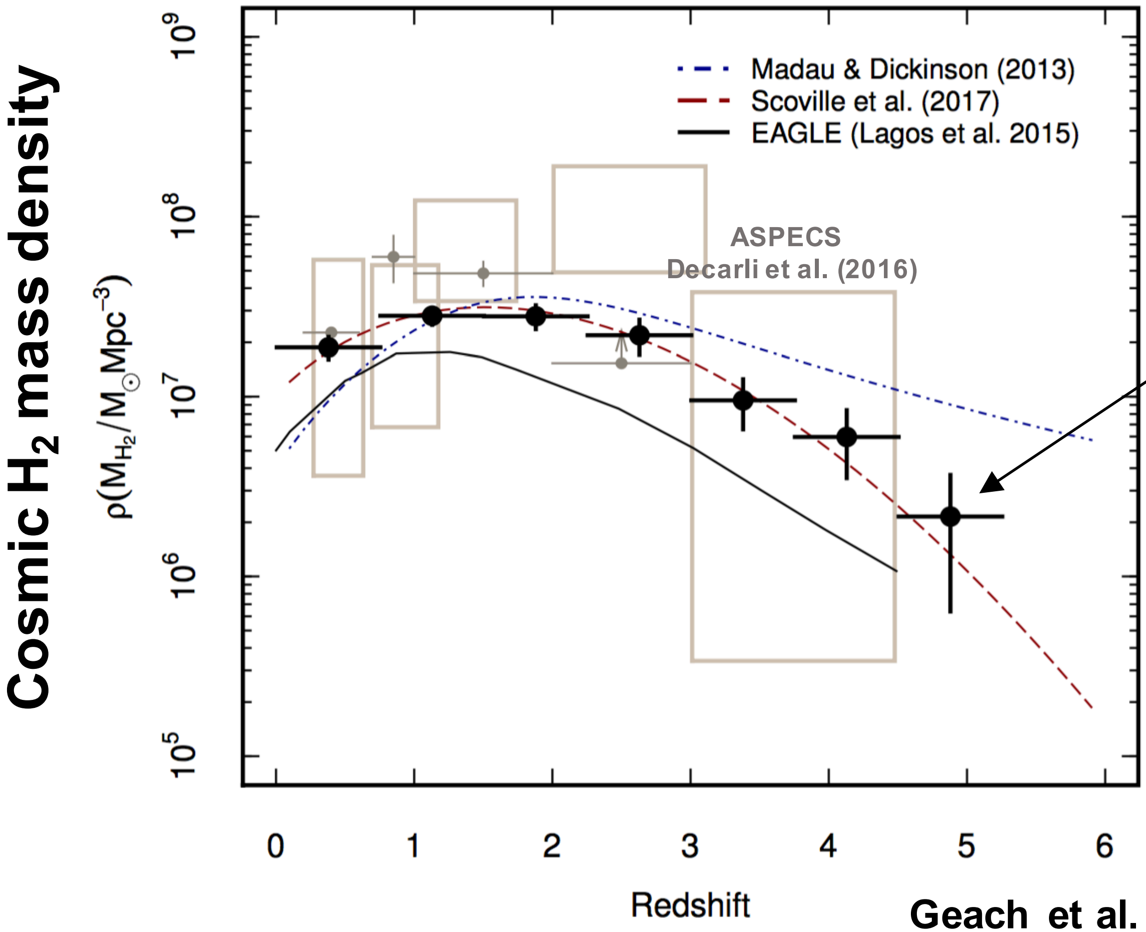
Scoville et al. (2017): yes, both ISM mass and SFR per unit ISM mass are increasing to high-z





Tacconi et al. (2017): only weak dependence on depletion time scale over z=0-2, "*MS star formation is driven by similar physical processes at high- and low-redshift*"

The epoch of molecular gas

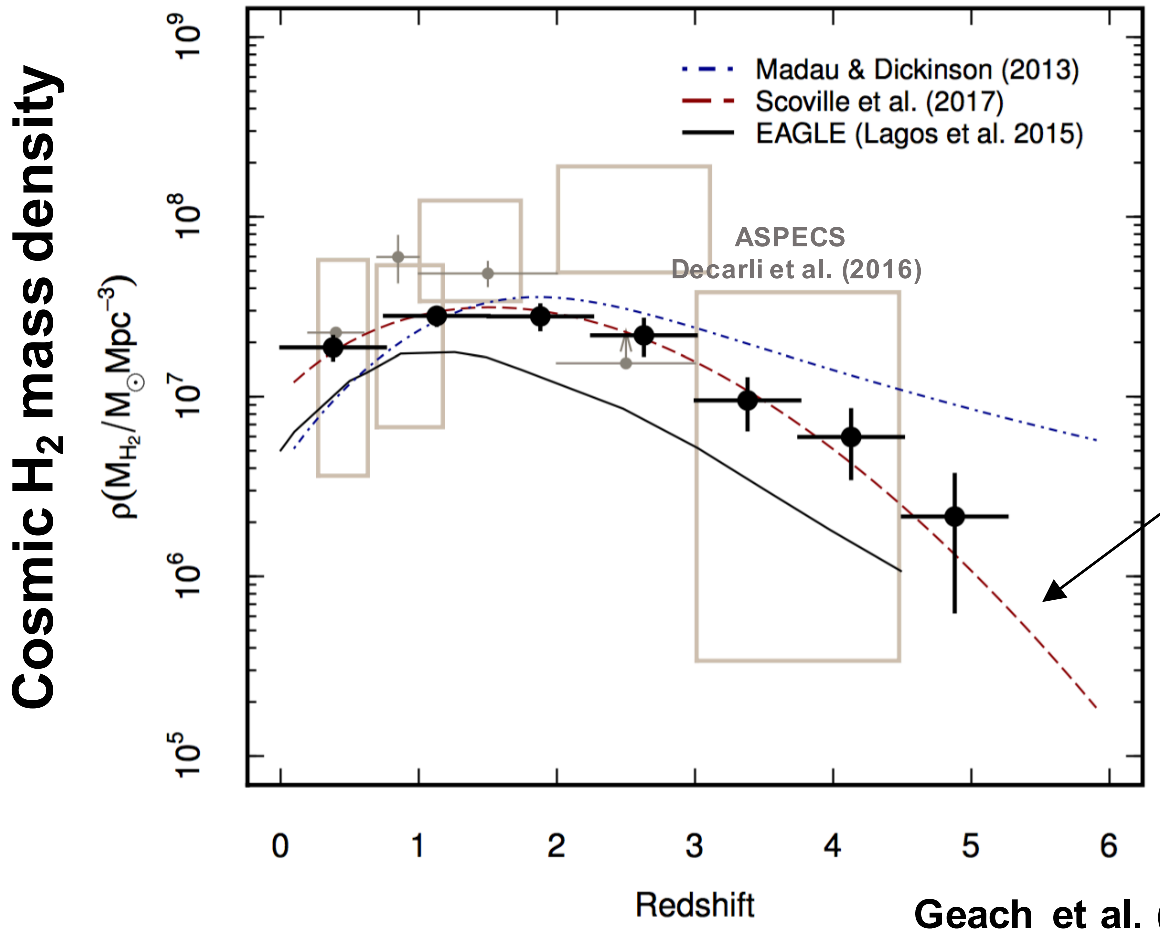


ISM mass estimate based on 3D stack of deep 850μm map at positions of K-band selected sources in UDS using Scoville RJ continuum-ISM mass calibration

$M_{*} \sim 10^{10}\ M_{\odot}$ galaxies

Geach et al. (2017, in prep)

The epoch of molecular gas

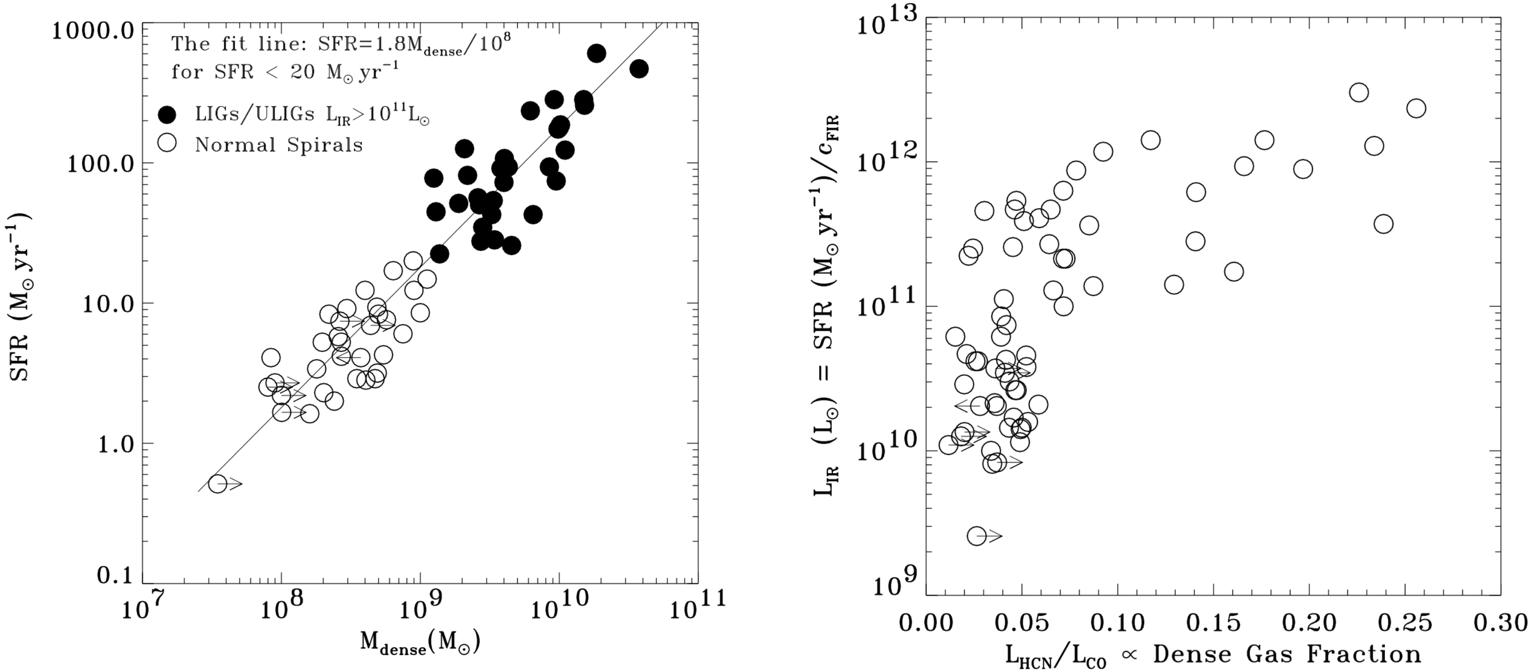


Scoville et al (2017) $M(H_2)$-M_* MS scaling + SHM + HMF + simple log normal halo occupation model for MS galaxies

Geach et al. (2017, in prep)

Does a higher (total) gas fraction necessarily drive higher star formation efficiency?

What really matters is dense gas fraction



Gao & Solomon (2004)

A simple model for star formation 'mode'

Geach & Papadopoulos (2012)

Assume ~constant SFE per unit *dense* gas mass

Observational evidence for this (Downes & Solomon 1998; Shirley et al. 2003; Scoville 2004; Thompson et al. 2005; Thompson 2009), consistent with radiation pressure limited SF

Galaxies vary by M_{dense}/M_{total} H_2 ratio (call it ξ)

SF only proceeds in dense gas, while some fraction remains quiescent. Typically only 1% of the disc reservoir converts to stellar mass per free fall time (t_{ff}) when averaged over galactic scales (Krumholz & Tan 2007)

Starbursts have ξ~0.5, quiescent discs ξ~0.05

ξ can be driven up through mergers, VDIs, etc. (Padoan & Nordlund, 2002)

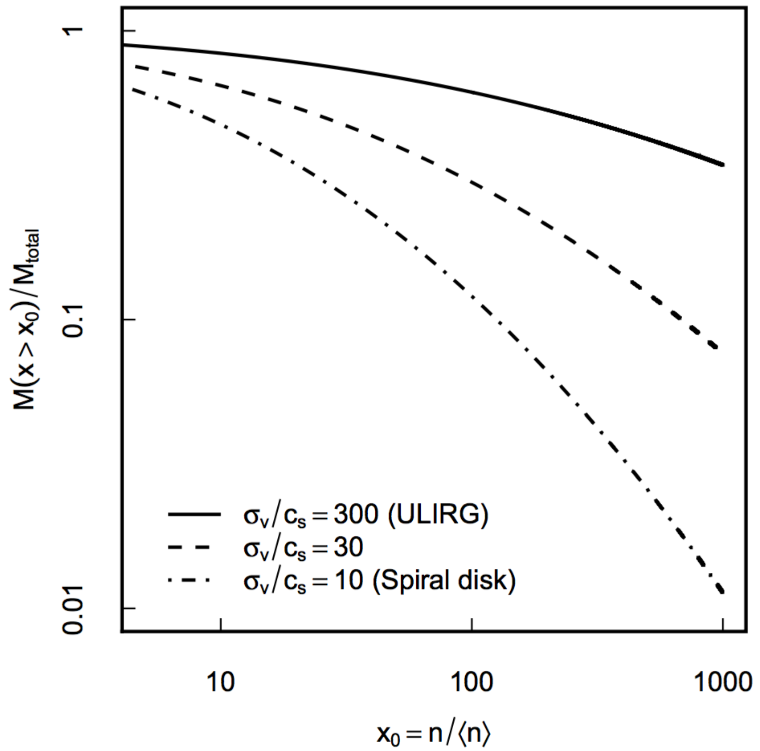
Can infer M_{total} given SFR and ξ

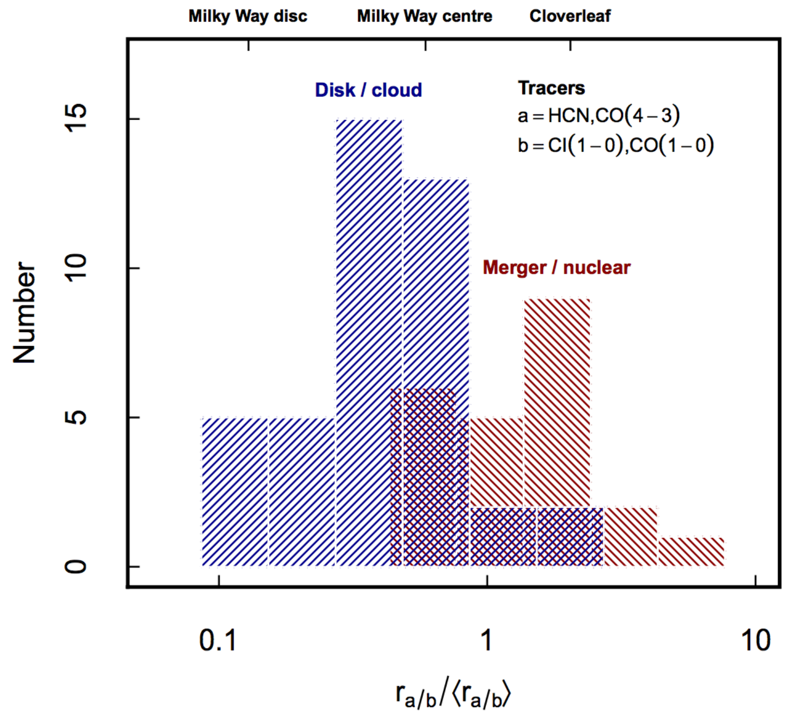
Papadopoulos & Geach (2012)

$$\xi_{\rm SF} = \frac{M(x \geq x_0)}{M_{\rm total}} = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{-2\ln(x_0) + \sigma_\rho^2}{2^{3/2}\sigma_\rho}\right)\right]$$

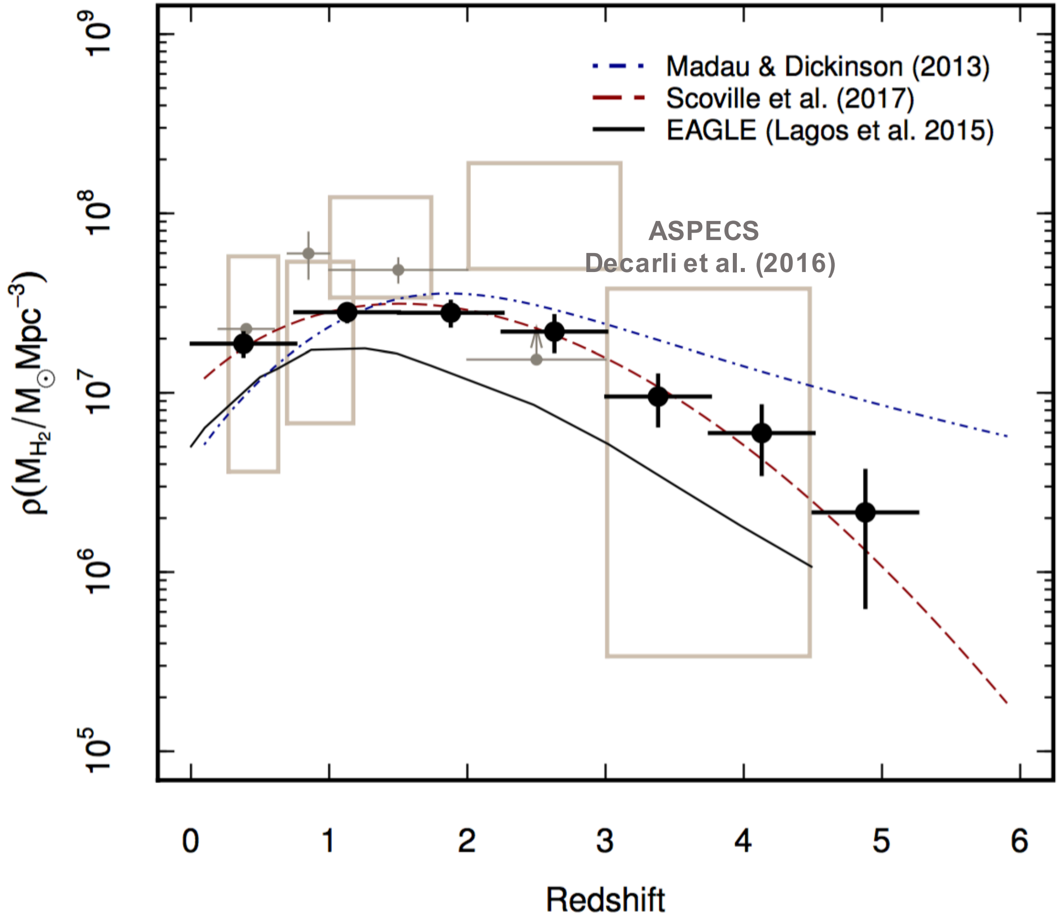
$$\sigma_\rho = \sqrt{\left(\ln\left(1 + 3\mathcal{M}^2/4\right)\right)}$$

Padoan & Nordlund (2002)





Dense-to-total gas mass ratio can be traced by numerous species, with CO(4-3)/[CI] accessible over most of cosmic time



ξ~5-10% average 'cosmic star formation efficiency' peak inferred from SFRD

Bulk of cosmic H_2 at z~2 is in galaxies with $M_* \sim 10^{10}\, M_\odot$

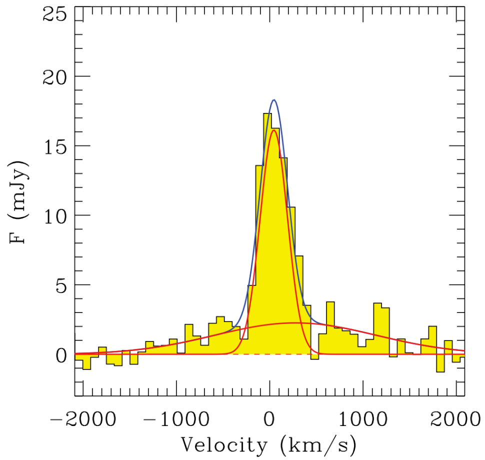
Note: Transition from gas phase to dust phase H_2 formation occurs z~3-6: positive feedback as metals enrich ISM (Cazaux & Spaans, 2004)

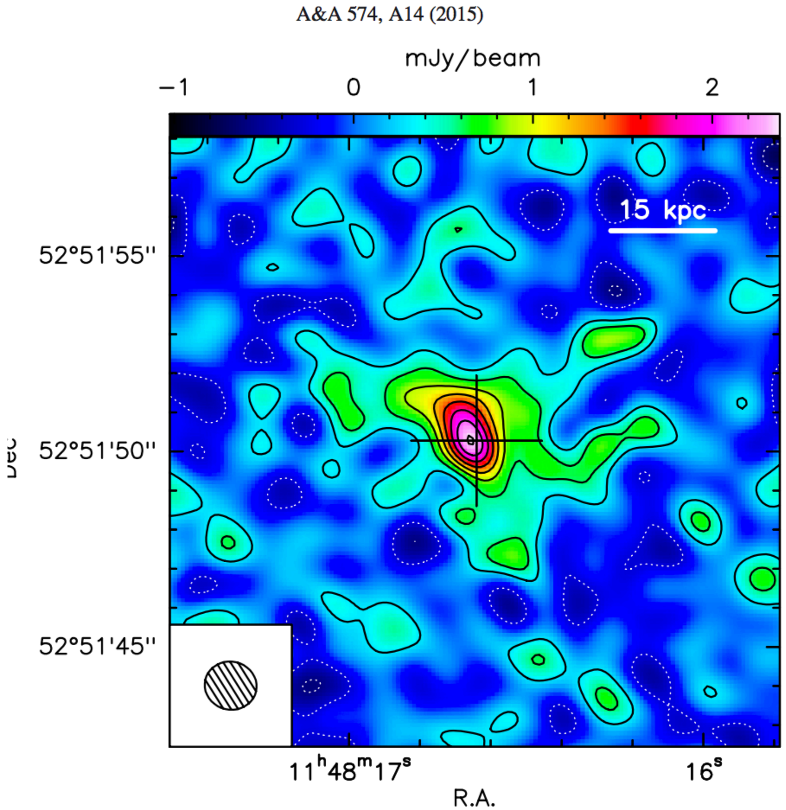
Feedback’s impact on molecular gas

Quasar mode feedback

Evidence that quasars are driving high velocity outflows of cold gas through observations of broad CO, [CII] lines

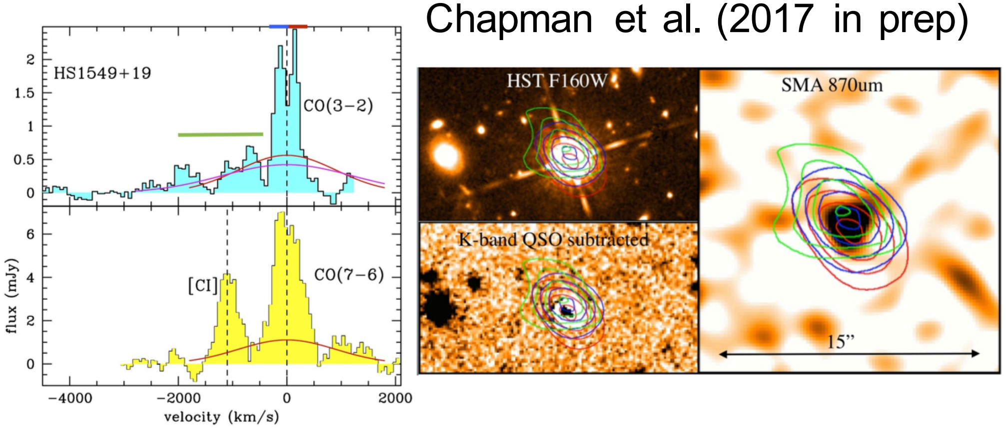
Maiolino et al. (2012)



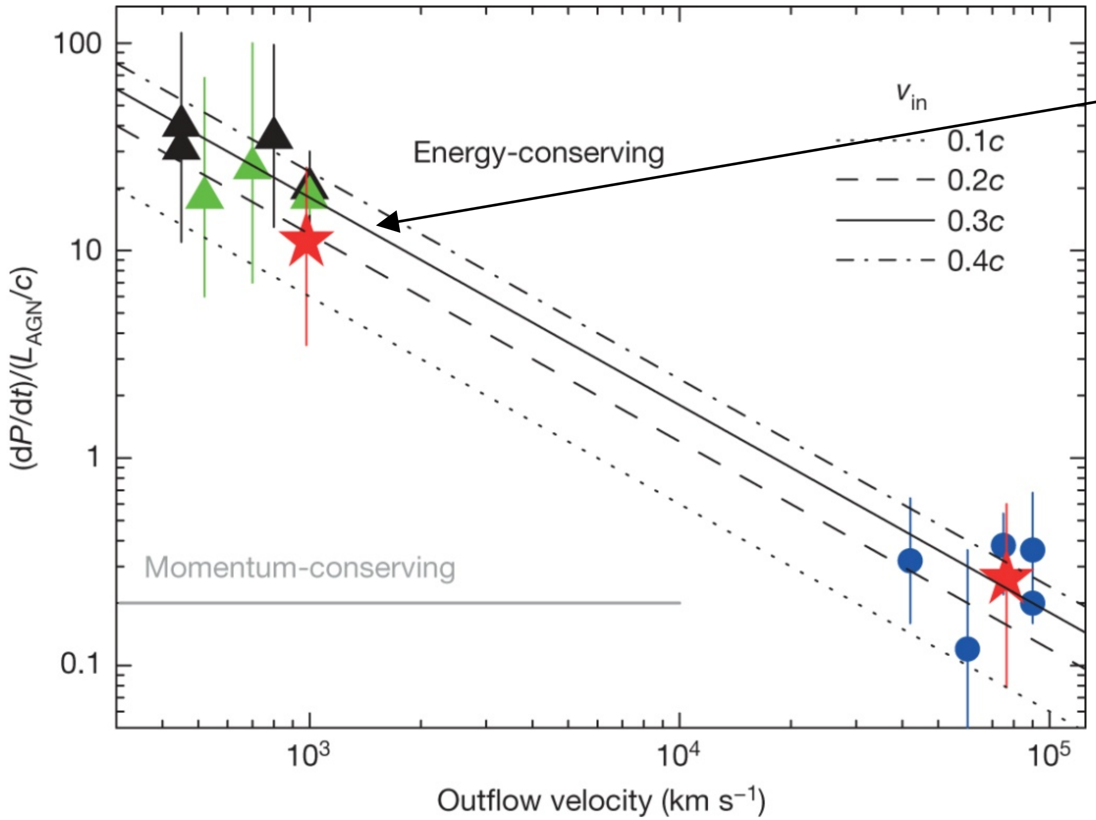


Cicone et al. (2015)

Chapman et al. (2017 in prep)



Coupling small to large scales



kiloparsec scale molecular (OH in this case) winds with ~100s km s^{-1}

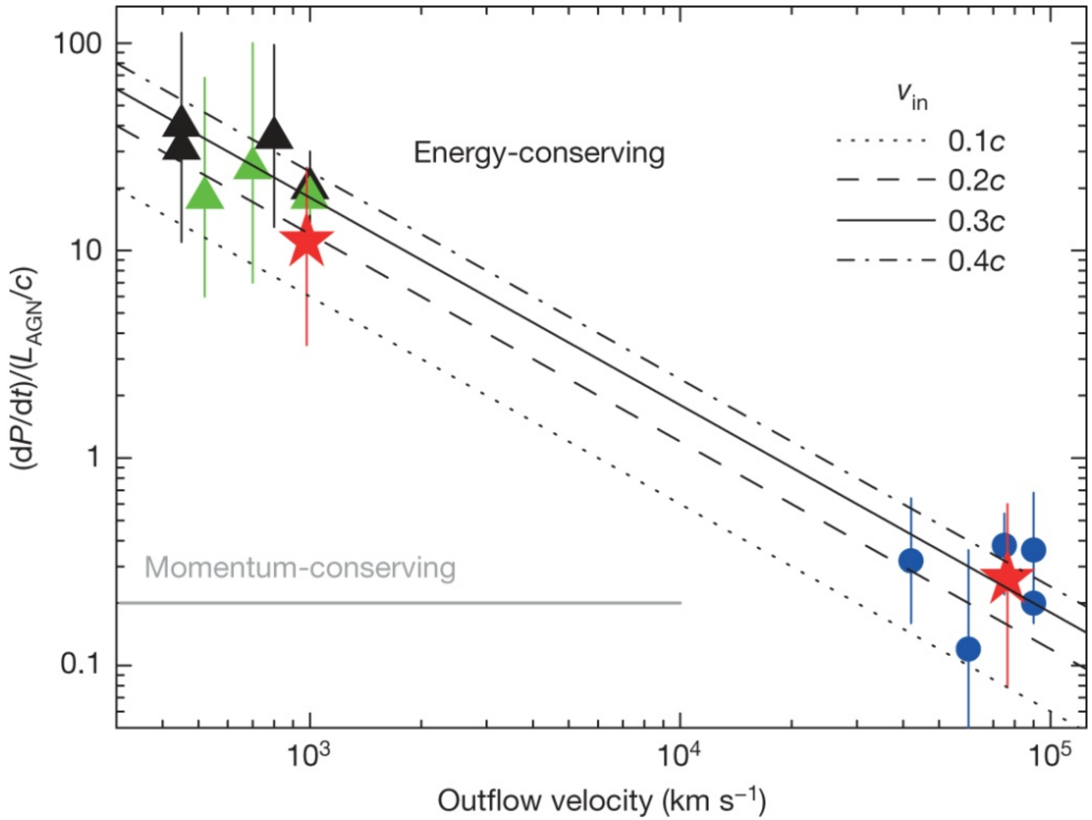
relativistic wind launched within ~few 100 AU from black hole

20% of the power of the inner wind is transferred to the large-scale outflow

IRAS F11119+3257

Tombesi *et al. Nature* (2015)

Coupling small to large scales



Tombesi *et al. Nature* (2015)

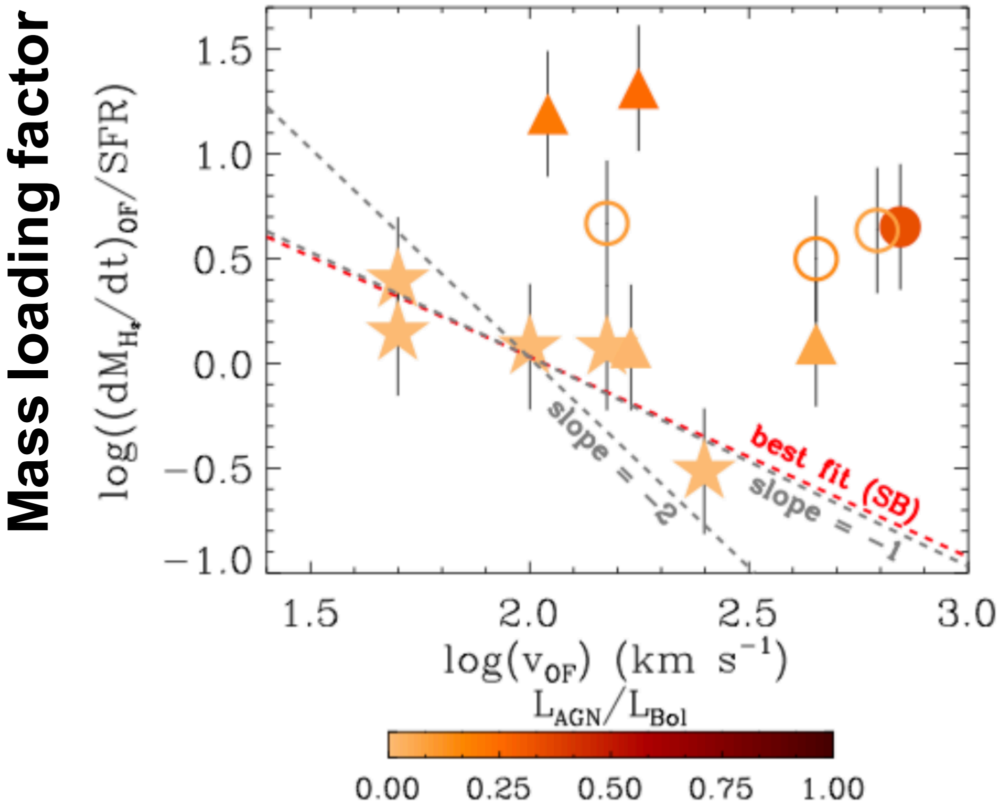
IRAS F11119+3257

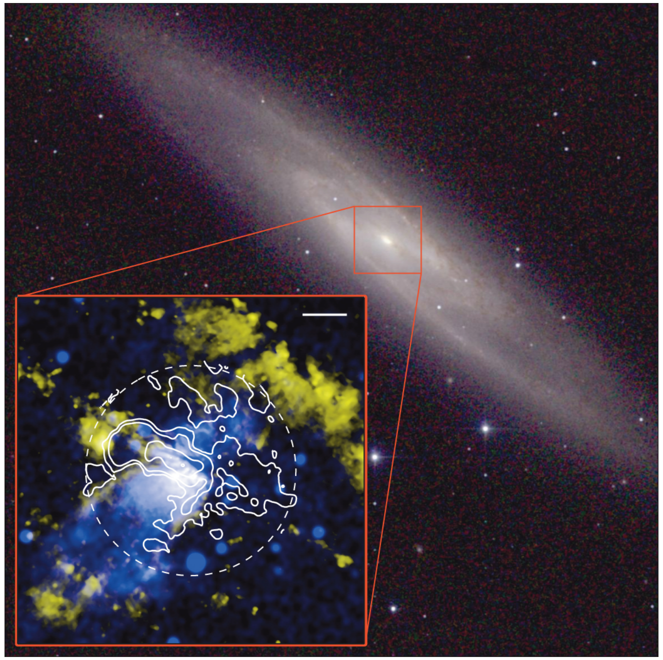
In a momentum-conserving outflow, thermal energy in the shocked wind is rapidly radiated away. If these losses are low, then the outflow is described as energy-conserving

Energy-conserving outflows are effective because they entrain more material, with P-dot increasing as the shock front propagates through the ISM

Pure stellar feedback

Cicone et al. (2014)





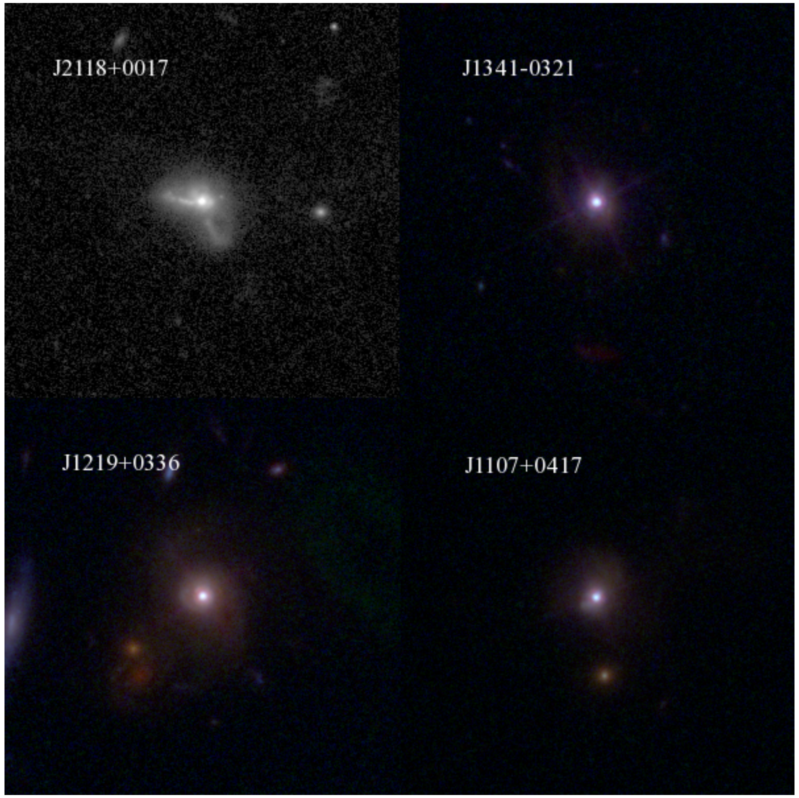
Bolatto et al. (2013)

In single scattering limit, momentum flux ~ L/c

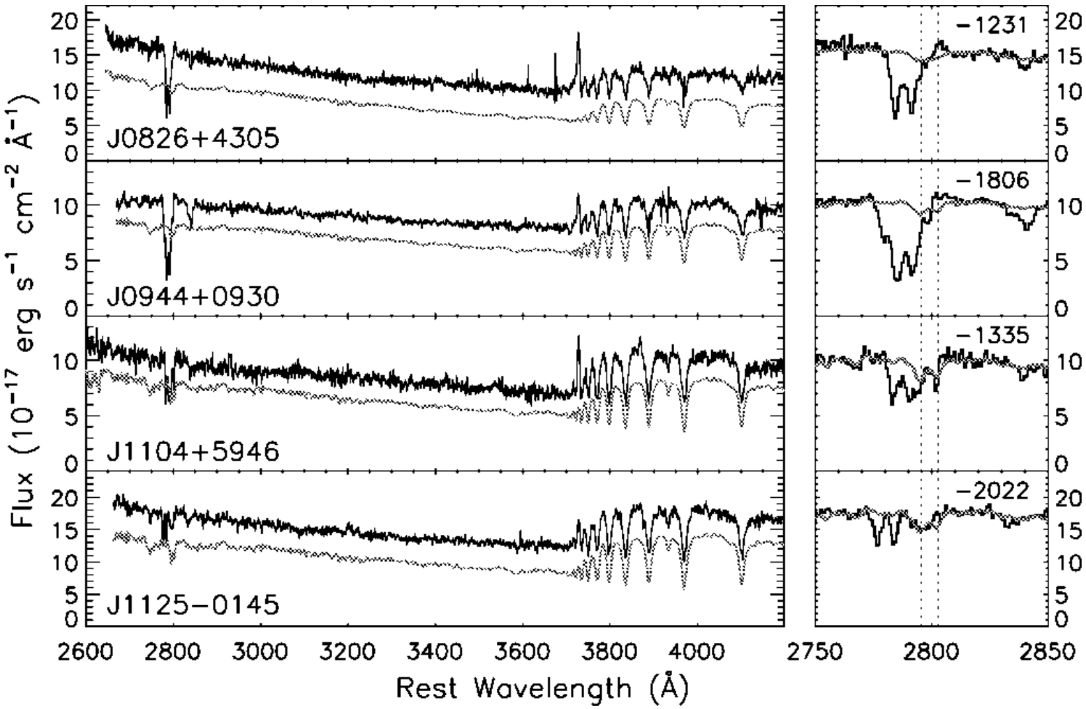
In a momentum driven wind, mass loading proportional to v^{-1} (Murray et al. 2005)

Presence of AGN boosts mass loading, but pure starburst can drive molecular wind

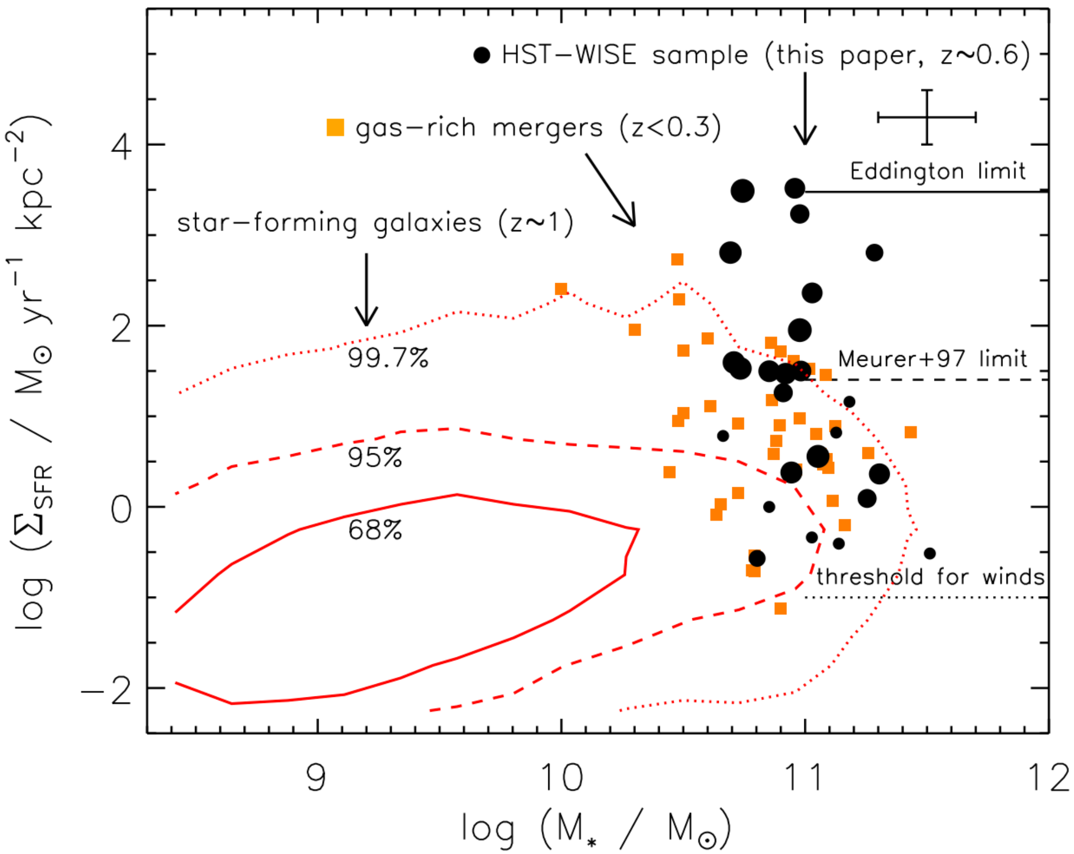
The most aggressive feedback



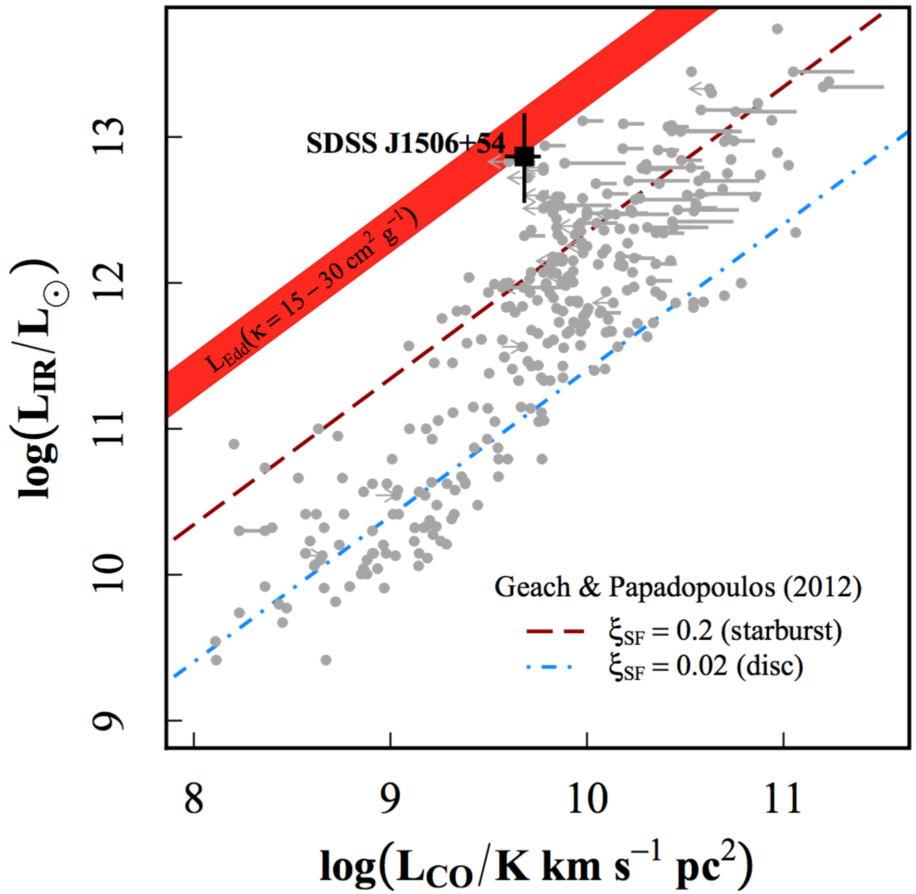
Sell et al. (2014)



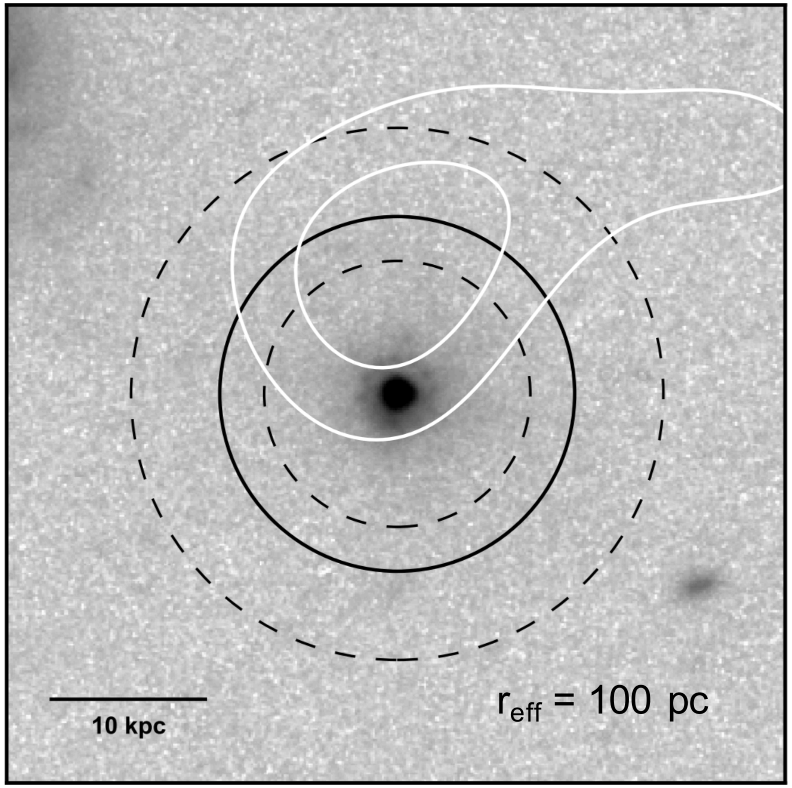
Tremonti et al. (2007), Diamond-Stanic et al. (2012)



Diamond-Stanic et al. (2012)

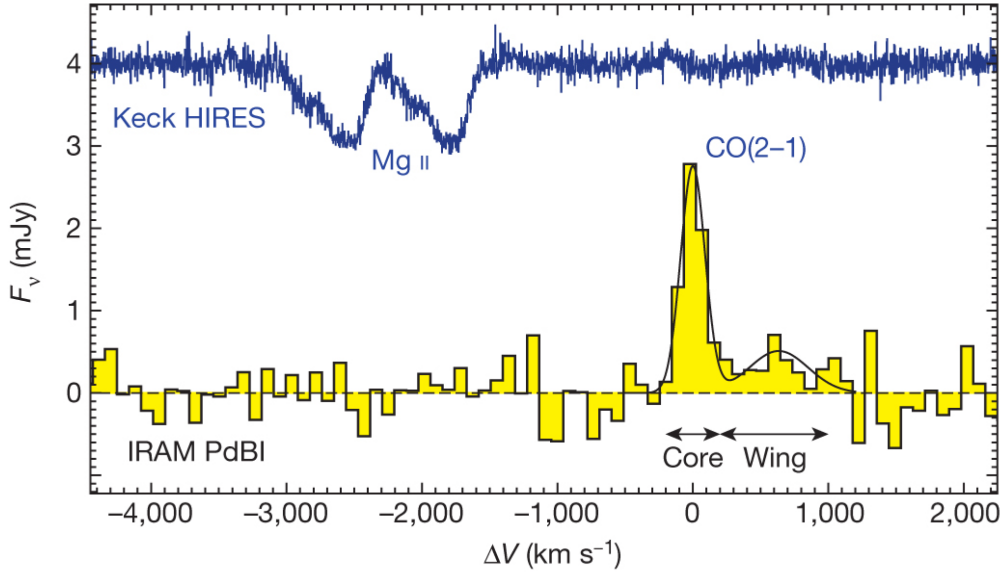


Geach et al. (2013)



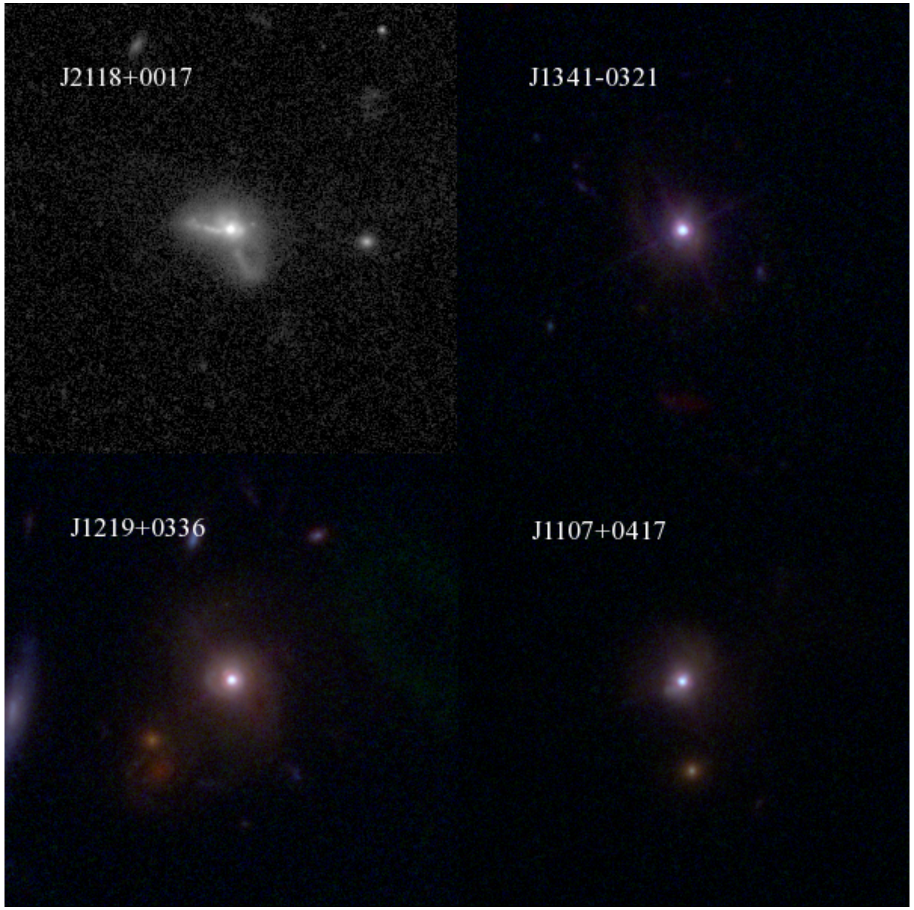
90% of stellar luminosity is from a population less than 10 Myr

Geach et al. (2014)



$$v\dot{M}_{\mathrm{H_2}} \approx (4.8 \pm 1.9) \times 10^{30}\,\mathrm{N}$$

$$\dot{p}_{\mathrm{rad}} \approx 4 \times 10^{30}\,\mathrm{N}$$



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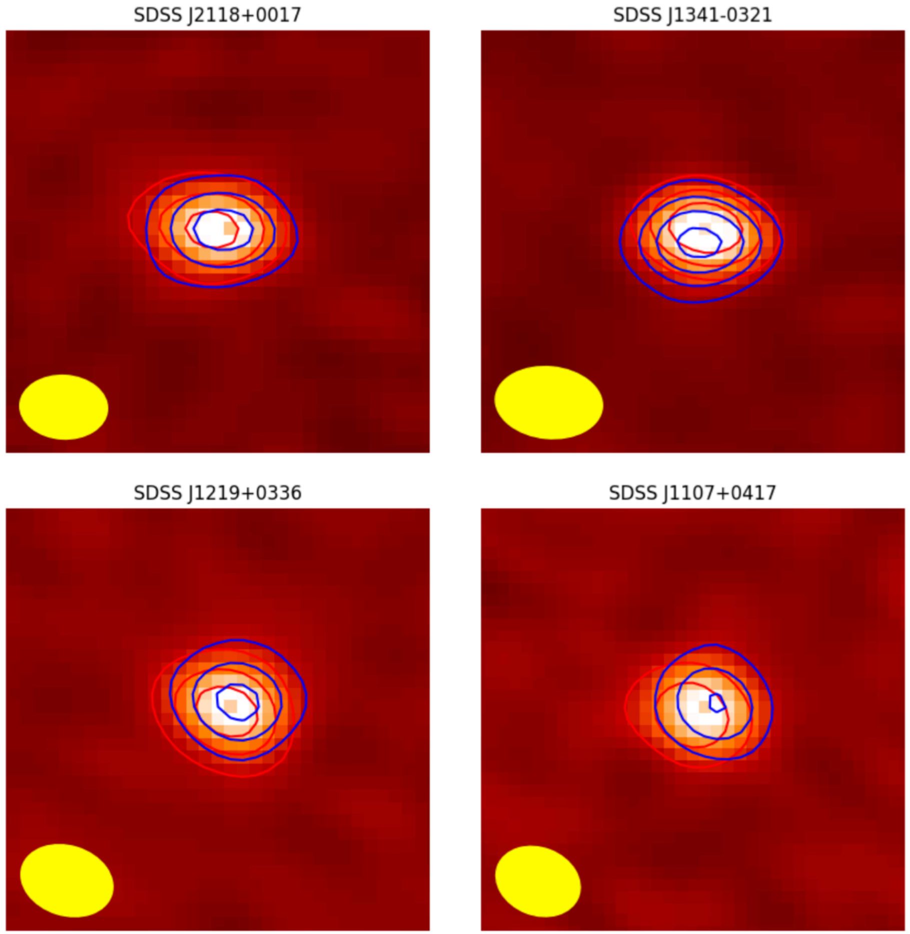
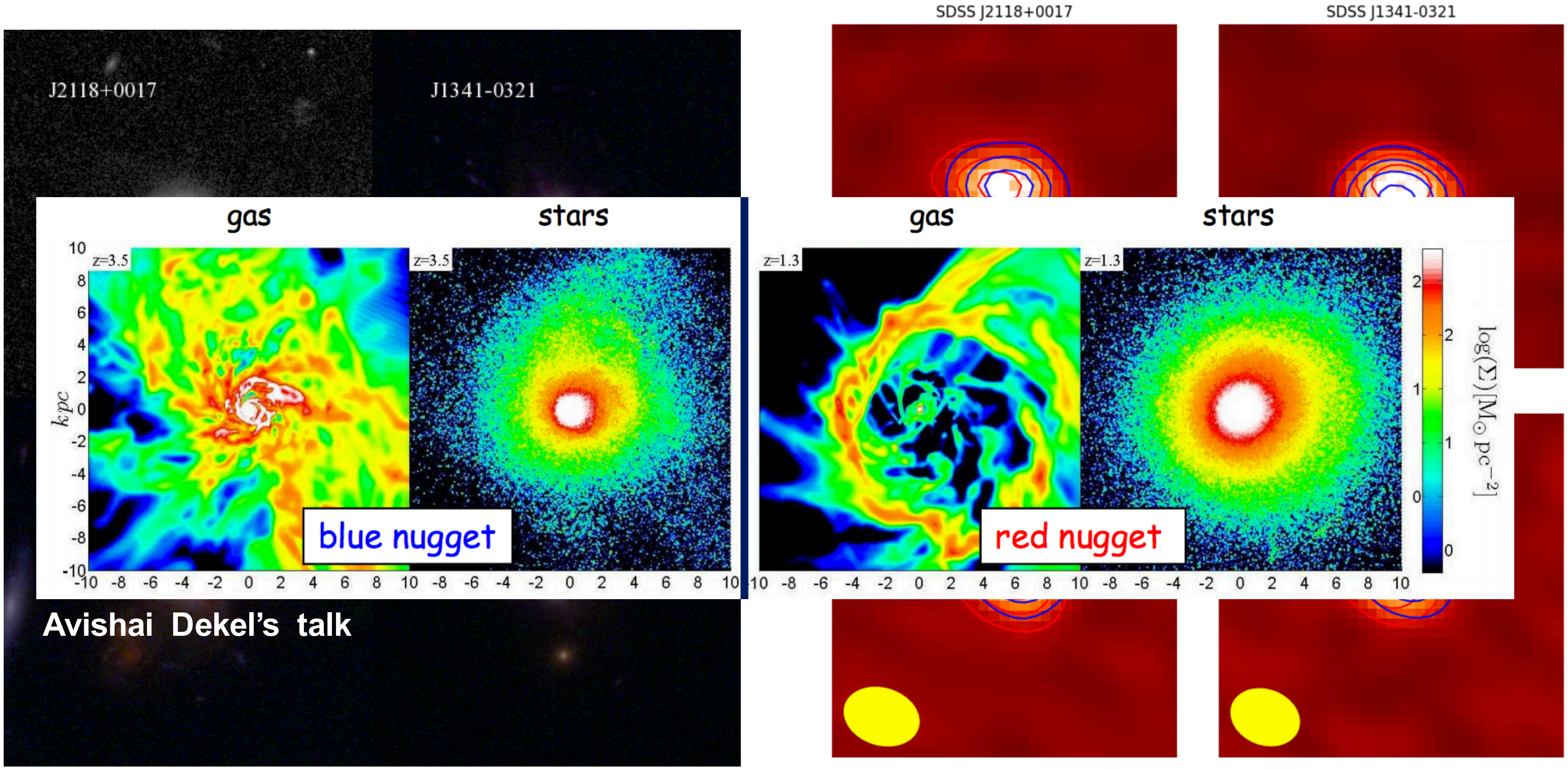


ALMA Cycle 4 results: CO(2-1) observations


SDSS J2118+0017
SDSS J1341-0321
J2118+0017
J1341-0321
gas
stars
gas
stars
z=3.5
z=3.5
z=1.3
z=1.3
kpc
blue nugget
red nugget
$\log(\Sigma)[M_\odot\,pc^{-2}]$
Avishai Dekel's talk

Take home points

0. Direct and blind mm observations of cold gas in distant galaxies has allowed us to establish the key scaling relations for gas mass

1. Epoch of H_2 was at z~2, with most of the gas in galaxies with $M_{*} \sim 10^{10}\,M_{\odot}$

2. Molecular gas fraction of MS galaxies increases to ~50% at z~2, but the star formation efficiency per unit gas mass may only be weakly increasing to early times

3. We can now observe how AGN and SF feedback impacts the cold ISM directly, giving insight into the mechanisms that actually regulate and truncate stellar mass growth